Geoacoustic Modeling: High-Frequency Scattering from Heterogeneous Rough Sea Beds at Shallow Grazing Angles (extension)

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LONG-TERM GOALS

The long-term goal of this research is to better understand the physics and mechanisms of sound-seabed interaction, including acoustic penetration, propagation, attenuation and scattering in marine sediments.

OBJECTIVES

The specific objective of this one-year extension project is to complete evaluation of the role of discrete scatterers for the complicated SAX04 environment, based on analysis of grain size distribution for coarse fractions (sediment inclusions) collected during SAX 04 acoustic experiment, and taking into account the stratified mud/sand structure of the SAX04 sediment.

APPROACH

There are different mechanisms of seabed scattering which are due to different types of seabed medium irregularities, which are roughness of the seabed interfaces, and volume heterogeneity: continuous (spatial fluctuations of the sediment acoustic parameters) and discrete scatterers (or sediment inclusions, such as relatively large shells and shell fragments). Given different environmental conditions, frequencies and angles of scattering, relative contributions of these mechanisms can be also different. For example, in the SAX99 situation, the contribution of the volume continuous heterogeneity was shown to be insignificant [1]. For the sediment rough surface scattering, first conclusion was that it is the dominant mechanism in a wide frequency range, roughly 20 kHz to 200 kHz. In later work, however, it was shown that the contribution of the volume continuous heterogeneity in SAX99 environment also can be important, particularly at frequencies above 50 kHz [2,3].

Acoustic backscattering from the sediments at SAX04 was quite different from SAX99 [4]. This was result of substantially different environmental conditions caused by known weather events preceding and during SAX04, and, resulting from these events, more complex structure of the SAX04 sediment [5]. In particular, an important complication is appearance of a thin but distinctive mud layer covering a sand basement. The thickness of the mud layer varied from a few mm (forming a thin transition layer

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14. ABSTRACT
The long-term goal of this research is to better understand the physics and mechanisms of sound-seabed interaction, including acoustic penetration, propagation, attenuation and scattering in marine sediments.

15. SUBJECT TERMS

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between water and sand) to about 5 cm (filling depressions in the sand rough surface). This, in particular, resulted in more flat surface of the sediment in comparison with SAX99.

The roughness spectra were measured on both boundaries of the mud layer and it was shown that the roughness scatter itself can provide only insignificant contribution to the observed scattering level [4]. Therefore, the SAX04 acoustic data analysis (unlike SAX99) can be narrowed down to volume scattering in the sediment, which includes two components, continuous and discrete. Effects of scattering from continuous volume heterogeneity of the SAX04 sediment were examined in [4]. Necessary inputs to the model of scattering were provided by measurements of vertical correlation functions of the sediment porosity and density [5]. It was shown that continuous volume fluctuations of the sediment acoustical parameters can provide a reasonable explanation of sound scattering at frequencies up to 130 kHz.

The main objective of this research is to examine the role of another component of volume heterogeneity, discrete scattering mechanism, for the SAX04 sand/mud environment. Discrete scatterers of the sediment can be defined as relatively large particles with the size noticeably larger than the mean grain size. These particles comprise only a small volume proportion of the sediment, and can be considered as sparse discrete “inclusions” in the sediment matrix. For the SAX04 predominantly medium sand sediment, the mean grain diameter was about 0.36 mm [5], and inclusions are all gravel-sized and larger particles, which mostly were carbonate shells and shell fragments. It is assumed that acoustic measurements of the seabed backscattering strength made at SAX04 [4] along with environmental characterization of the sediment at this site [5] and, particularly, analysis of the sediment inclusions [6] can provide a necessary ground truth for this study.

It should be noted that existing models of scattering from inclusions, such as those developed for the SAX99 environment [2,3], require a significant modifications before being applied for the SAX04 data analysis. In particular, they should take into account two major complications. First one is due to the essential stratification of the SAX04 sediment. Development of a model of discrete scattering for stratified sediments is one of the goals of this project. Another modification is required for existing algorithms of the grain size analysis, to provide adequate input parameters for the “inclusion” scattering models. This is because the particle size distribution (the number of particles in each size class), required in models of scattering, is defined in traditional algorithms assuming that particles are nearly spherical. Such assumption allows the number of particles in each size class be determined from their total volume or weight. However, large inclusions, such as shells and shell fragments, which are the main interest in this work, are essentially non-spherical, and existing techniques not applicable for them. To develop modified algorithms of non-spherical particle characterization, relevant to acoustic modeling for the SAX04 environment, is another goal of this project.

WORK COMPLETED

Modified algorithms were developed for granulometric analysis of the SAX04 sediment samples, to infer input parameters required for the scattering models. For this, the PI has analyzed particles of coarse fractions with the sieve size greater than 1 mm from several sediment samples taken at the SAX04 site. These include ten cylindrical samples of 20 cm diameter with total volume about 19 liters that were collected by divers and contained the sediment of the upper 6 cm layer. Also, a larger

volume of the sediment (about 160 liters, from the upper 0 to 18 cm divided on three layers 6 cm each) was excavated during deployment of the APL-STMS1 apparatus (the cofferdam sediment). This sediment was placed in bags with 1.6 mm mesh and pre-sieved by shaking underwater.

For all the collected samples and the cofferdam sediment, using a set of sieves with the quarter-phi interval of the screen openings (sieve size), the coarse fractions of sediment particles were analyzed by the grain size. Then two visually different types of grains, coarse sand particles and shells (mostly shall hash), were segregated from each other and analyzed separately in each size class (with quarter-phi intervals). The parameters of these two types of particles, their number, weight and volume per grain, equivalent spherical size, and a “shape factor”, were determined as functions of the sieve size in the 1 to 20 mm sieve size range.

The “inclusion scattering” model has been further developed for the complex SAX04 environment, in particular, to include effects of the sediment stratification. This model has been described in detail in [7], and applied to analysis of the SAX04 seabed scattering data obtained by K. Williams [4]. The size distributions of inclusions obtained in [6], and the stratified sediment parameters given in [5], were used as inputs to the scattering model to provide model/data comparison for the SAX04 multi-frequency backscatter data.

RESULTS

The main results of this project are described in two papers submitted for publication [6,7].

1) *Sediment Particle Characterization for Acoustic Applications: Coarse Content, Size and Shape Distributions in a Shelly Sand/Mud Environment* [6].

In this paper, the traditional weighing-sieving techniques were significantly modified to provide corrections for essentially non-spherical shape of coarse particles. Acoustic scattering models require knowledge of the number-size distribution of the coarse sediment particles (inclusions). The SAX04 sediment particles can be described as a mixture of two populations, represented by carbonate (shells) and quartz (sand) particles, with different densities, shape ad size distributions. The size distribution histograms and cumulative functions were determined for sieve sizes 1 mm and larger, at quarter-phi intervals. Size distribution of quartz particles decrease much more steeply, as the size increases, in comparison with the size distribution of shells. This resulted in domination of quartz particles over carbonate (shells) in the coarse sand and smaller size range, while shells are dominating in gravel and larger size range. Generally, shells can be considered as sparse inclusions in a sediment matrix comprised of sand particles.

Shells and shell fragments are shown to have also very different shape than sand particles. To quantify the particle shape, a shape factor was introduced as a ratio of two volumes, that for a sphere having the same sieve size, and actually measured average volume of particles in this sieve size class. Upon segregation of quartz and carbonate particles, from comparison of the independently measured distributions of the particle volume and sieve sizes, the shape factor was determined. This new technique allowed a simple quantification of a “typical shape” of particles to replace the “spherical shape” assumption, and therefore to provide an improved estimation of the particle number size

distribution. It allows also defining the equivalent spherical diameter, or the particle “true size”, and its empirical relationship with the “sieve size”.

The “true size” cumulative distribution for relatively small part of largest particles was determined also independently from a grain-by-grain analysis, not using traditional sieving techniques. The comparison with the sieve-size distributions showed a noticeable discrepancy, which was used to test proposed sieve-true size empiric relationships for the non-spherical particles. Using these empiric relationships, a method of correction for the sieve size distributions was presented, and eliminating the discrepancy was achieved and illustrated. The true size distributions of coarse particles obtained in this paper are capable of giving a more adequate sediment characterization for acoustic applications, particularly, to provide necessary input parameters for modeling of the seafloor scattering. Fig.1 presents results of this analysis for the size distribution of shells as function of their equivalent diameter, “true size”. A remarkable feature of this size distribution is that it very closely follows a power law in a rather wide range of sizes. Parameters of this distribution are critical inputs to the inclusion scattering model described in [7].

2) *Scattering from Inclusions in Marine Sediments: SAX04 Data/Model Comparisons* [7].

In this paper, the “inclusion scattering” model is described in detail and used for analysis of backscattering data obtained by K. Williams [4] during the SAX04 sediment acoustics experiment. The model assumes that scatterers are sparse discrete inclusions (such as shells and shell fragments) randomly distributed in the supporting continuous sediment matrix. Correspondingly, the model is comprised of two parts. First one describes the sediment matrix as an arbitrarily stratified “effective fluid” medium defined by vertical profiles of its acoustic parameters, the density, sound speed and attenuation. According to recent analysis [5], these profiles at the SAX04 environment can be chosen as continuous functions corresponding to a mud-to-sand transition layer over a sand half-space, see Fig.2.

Second part of the model describes the inclusions in terms of the individual scattering functions and the number-size-depth distributions. The number-size-distribution of shell inclusions is described in [6], see Fig.1. The depth-distribution of inclusions at the SAX04 environment is generally rather complicated. The origin and mechanisms of this complexity are described and discussed in [4,5]. In Fig.2, the depth-distribution of scatterers, which was considered for following calculations, is illustrated. It includes three different (with regard to their depth) types of inclusions. These inclusions are (1) shells in the sand basement half-space, (2) shells located in a thin layer inside a mud-to-sand transition layer, and (3) sand particles in the top mud layer. Each of these three types of inclusions represents an important scattering mechanism in different ranges of frequencies and grazing angles.

Results of calculations for the bottom backscattering strength due to these three types of inclusions and data/model comparisons are presented in Fig. 3, and Fig. 4. Fig.3 shows the frequency dependencies at different fixed grazing angles. It demonstrates how relative contributions of the three types change with changing the frequency and angle. For small grazing angles, 20 and 25 degrees and all frequencies (top two subplots), scattering from mud-to-sand transition layer is dominating, due to contributions of shells (at frequencies below about 200 kHz) and sand particles (above 200 kHz). For larger grazing angles, 30 and 35 degrees (two bottom subplots), shells located within the sandy

basement dominate at frequencies below about 250 kHz. The model/data comparison gives quite a reasonable fit for almost all frequencies and grazing angles, with except of small angles (20 to 25 degrees) and lowest frequencies (30 to 40 kHz). Fig.4 shows angular dependencies for the three types of scatterers at different frequencies and confirms these conclusions. Again, the greatest discrepancy is seen at 30 kHz and small grazing angles (the top left subplot).

The main result of this data/model comparison is that not only the level of scattering by the SAX04 sediment inclusions is comparable with the observed level, which itself proves that the sediment inclusions indeed can play a noticeable role in the SAX04 seabed scattering. This model provides also a good explanation of almost all noticeable features in frequency-angular dependencies of the SAX04 backscatter. Such features are: a remarkable change of frequency dependence behavior at about 200 kHz (see Fig. 3), sharp change near critical angle (about 30 degrees) and flat behavior at smaller angles for angular dependence (see Fig. 4, the 70 and 90 kHz data), disappearing critical angle effect at highest frequencies (see Fig. 4, the 200 to 400 kHz data).

A substantial discrepancy in the model/data comparison appears at lower frequencies and smaller grazing angles (see top left subplots in both Fig. 3 and Fig. 4). This can be result of neglecting another possible scattering mechanism, which can be due to sand lenses in mud, whose existence is noticed in [5], but was ignored in this work. This scattering mechanism is somewhat similar to that due to continuous heterogeneity of the SAX04 sediment considered in [4], but only to a limited degree. This limitation is because of a discrete-like spatial distribution of such lenses, which makes their statistics quite different from that for continuous heterogeneity. If this statistics or the spatial distribution of the lenses were known, a more consistent approach would be to consider them as another kind of discrete scatterers. The theoretical approach for such consideration would be quite similar to that developed in this work. However, the necessary information on such distributions is currently not available.

IMPACT/APPLICATIONS

This work has demonstrated that the sediment grain size distribution “tails”, corresponding to particles with sizes noticeably greater than the mean grain size, or the sediment inclusions, are critical characteristics and important factors affecting seabed scattering properties. This can have an impact on the very principles of development of the sediment data bases for geoacoustic characterization of the seafloor, which is the main focus of several Navy-sponsored programs, such as Ocean Bottom Characterization Initiative (OBCI). The model of discrete scattering from inclusions in arbitrary stratified sediment can be applied, for example, to upgrade existing models and codes used for predicting bottom reverberation, such as GABIM.

RELATED PROJECTS

This work is closely connected to other projects supported by the ONR-OA SAX04 program and strengthens its modeling component. This work was conducted in collaboration with investigators at the Applied Physics Laboratory, University of Washington (Drs. D. Jackson, K. Williams, E. Thorsos and others) and NRL (Drs. M. Richardson and K. Briggs).

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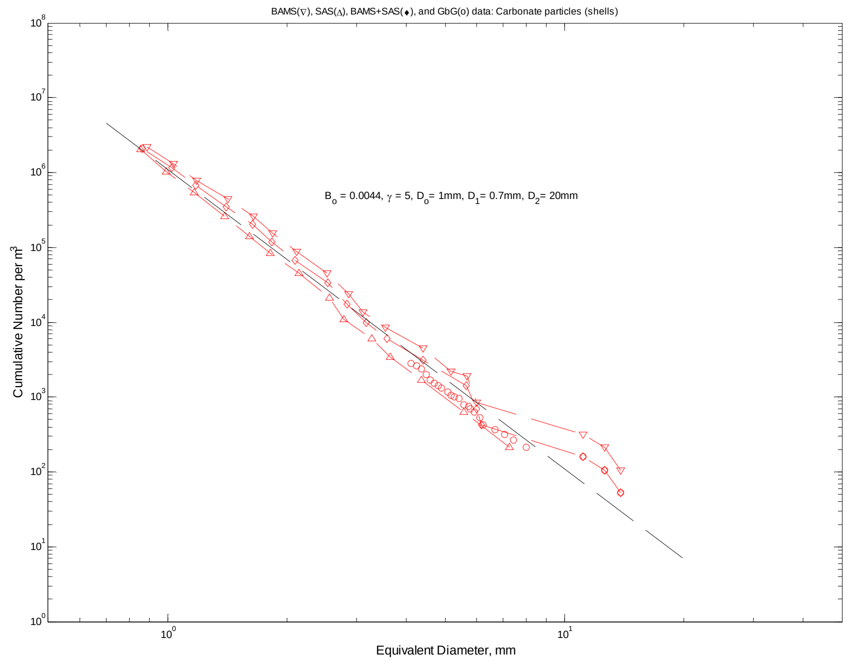

Fig. 1. Number-size distribution for the SAX04 sediment inclusions (shells) obtained from ten cylindrical (20 cm diameter, 6 cm vertical) sediment samples.

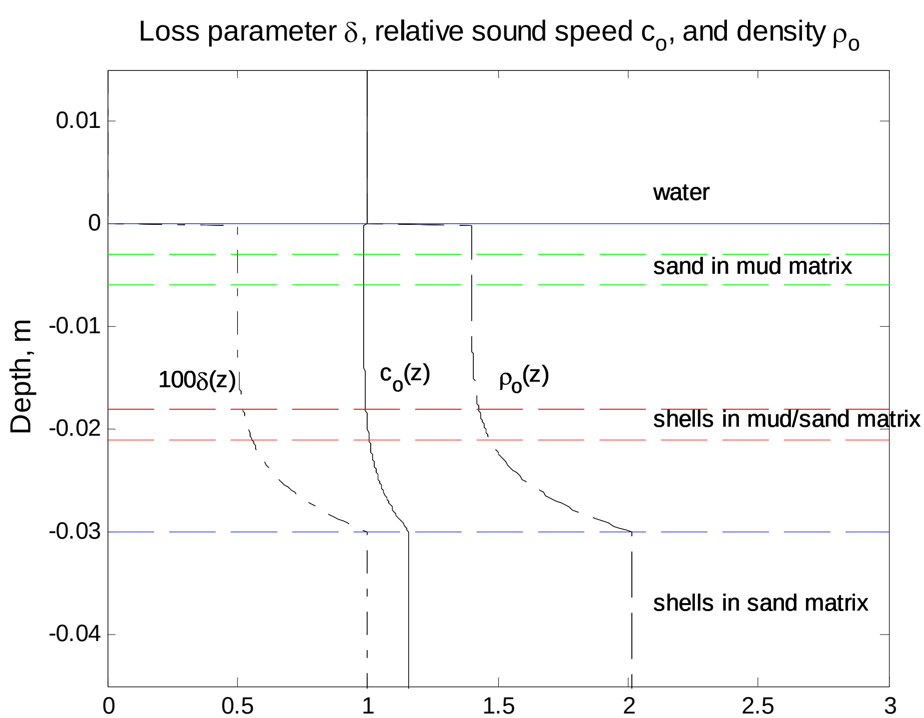

Fig. 2. A geoacoustic model of SAX04 sand/mud environment, defined by depth-dependencies of the density, sound speed and attenuation, taken for calculations of the bottom backscattering strength in data/model comparisons. Inclusions are (1) shells in the sand basement, (2) shells located in a thin layer inside a mud-to-sand transition layer, and (3) sand particles in the top mud layer.

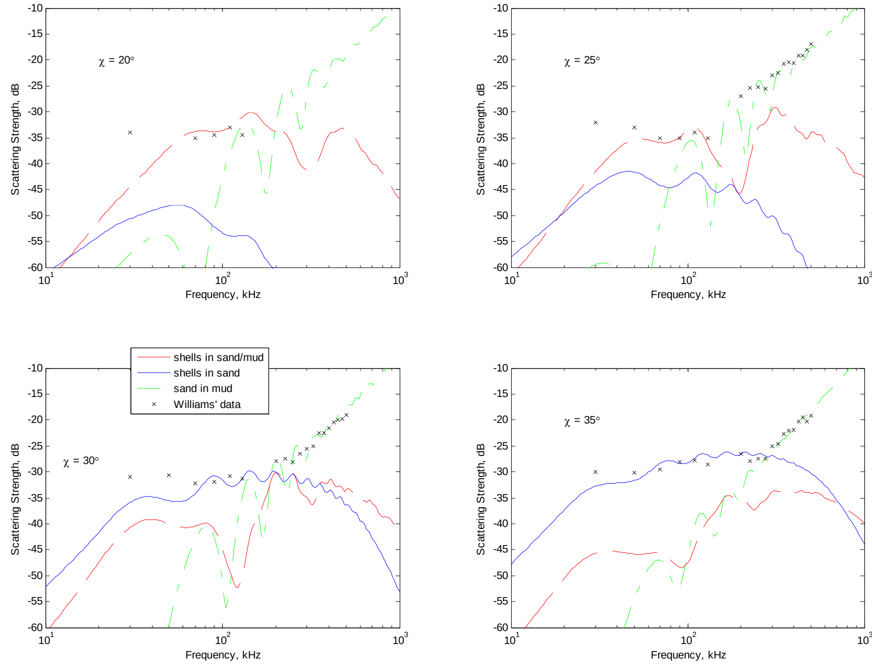

Fig. 3. Model/data comparisons: theoretical frequency dependences of the bottom backscattering strength for the three types of inclusions, shown at different grazing angles, 20, 25, 30, and 35 degrees, versus data measured at SAX04 by K. Williams [4].

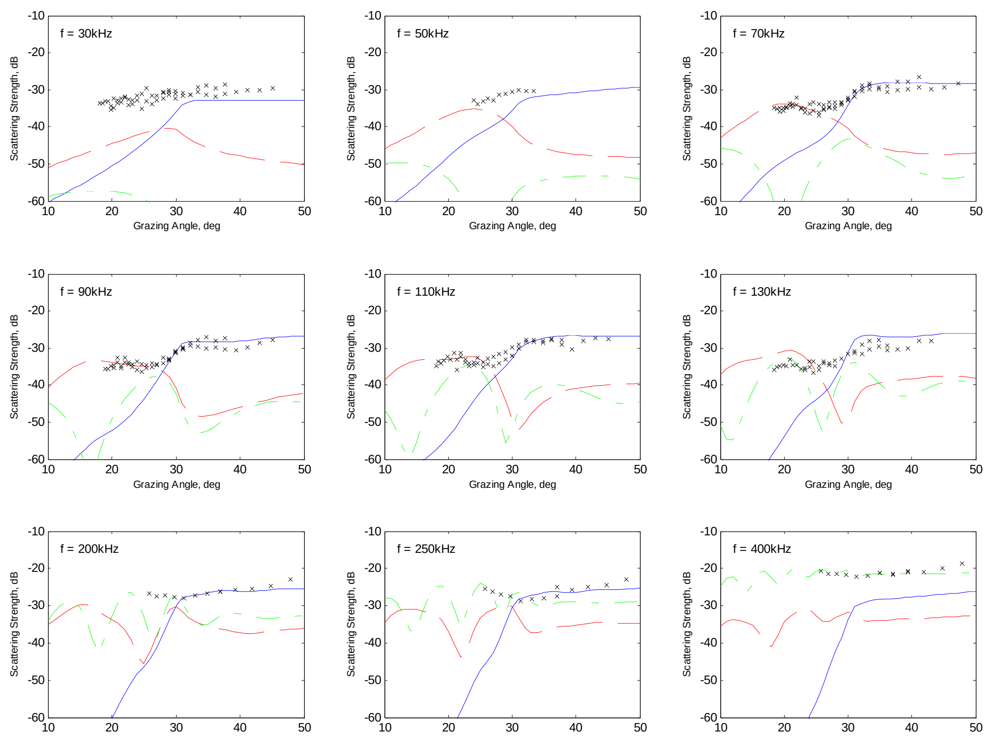

Fig. 4. Model/data comparisons: theoretical angular dependences of the bottom backscattering strength for the three types of inclusions, shown at different frequencies, 30 to 400 kHz, versus data measured at SAX04 by K. Williams [4].